Enabling low-loss thin glass solutions for 5G/mm-Wave applications

By David H. Levy, Shelby F. Nelson, Aric B. Shorey, Paul Ballentine [Mosaic Microsystems]

Thin glass substrates with fine-pitch through-glass via (TGV) technology provide attractive solutions for radio-frequency (RF) front end/5G, wafer-level packaging, microelectromechanical systems (MEMS) and systems integration [1-5]. High-quality glass can be formed in very thin sheets (<100µm thick) that enables solutions with a small footprint, and eliminates the need for back-grinding operations. Electrical and physical properties of glass have many attractive attributes such as low RF loss, the ability to adjust thermal expansion properties, and low roughness with excellent flatness to achieve fine lines/spaces (L/S). Furthermore, glass can be fabricated in panel format to reduce manufacturing costs.

The biggest challenge to adopting glass as a packaging substrate has been the existence of gaps in the supply chain, caused primarily by the difficulty in handling large, thin glass substrates using standard automation and processing equipment. This paper presents the Viaffirm® temporary bonding technology that allows thin glass substrates to be processed in a semiconductor fab environment without the need to modify existing equipment. We provide an overview of the handling technology along with its advantages, and demonstrate its successful implementation within the supply chain.

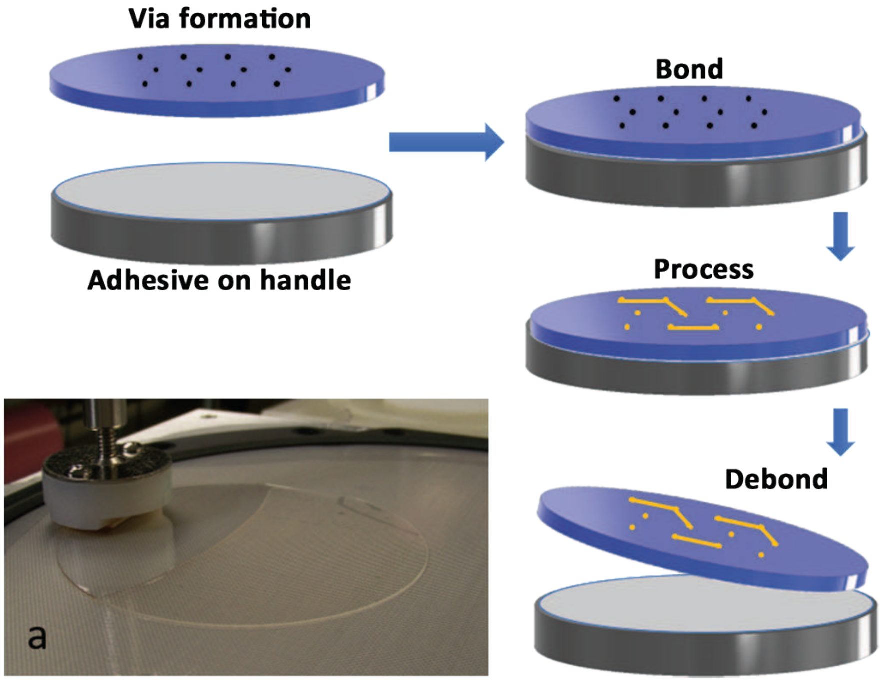

Figure 1: Depiction of temporary bond flow including bonding, process steps and the debond operation. The photo (inset a) shows the image of a debond operation on a bonded pair containing a fused silica device wafer bonded to a fused silica handle.

Introduction

The advantages include low insertion loss relative to Si-based solutions because when the operating frequency increases above a few GHz, silicon has high electrical losses, and also because of higher integration density compared to laminates and ceramics. Furthermore, research has shown the ability of glass to pass typical reliability testing including thermal shock and drop tests [6-7]. The challenge has been addressing how to make the transition from small-scale demonstration to providing solutions compatible with a high-volume manufacturing (HVM) environment.

To address HVM, a thin-glass handling strategy utilizing Viaffirm® temporary bond enables glass processing in the existing manufacturing infrastructure. The approach utilizes a thin inorganic adhesion layer to temporarily bond a thin glass device wafer to a silicon or glass handle wafer (Figure 1). Utilizing a Si handle, in particular, allows the thin glass to be processed with existing equipment and process flows, followed by only a mechanical debond to yield finished substrates.

While the handling solution is compatible with many glass types, two in particular are discussed here. One type is thin aluminoborosilicate glass, which provides an inexpensive large-area substrate with good surface properties. The aluminoborosilicate used in this study is Corning's Willow® glass. The second glass type is high-purity fused silica, obtained by thinning of commercially-available starting wafers. Below, we discuss numerous important aspects of these high-quality glass substrates containing TGVs, and highlight key technology advances including advances in handling. These advances are critical steps enabling the readiness of glass products for high-volume applications.

While glass is generally advantaged for RF packaging, fused silica is particularly well suited to 5G/mm-Wave applications because of properties like its low loss tangent. To demonstrate the usefulness of the thin glass structures possible with a good handling solution, we finish with recent simulations of low-profile fused-silica-based mm-Wave antennas, compared to analogous structures fabricated with printed circuit board (PCB) technology.

Application to TGV systems

The following sections discuss glass types and via formation, as well as the via fill and processing steps.

Overview of glass types and via formation. In this paper we focus on two different glass types with our temporary bonding system: high-purity fused silica (HPFS) and Willow®. From a standpoint of RF properties, the fused silica has one of the lowest loss tangents in the 10-50GHz range relevant to 5G communications. However, fabrication of substrates thinner than or equal to 200µm requires thinning of the thicker commercially-available fused silica. Additionally, the low CTE of fused silica (~0.6ppm/°C), while generally a desirable property, requires the use of relatively expensive fused silica handles in the temporary bonding framework. However, because the Viaffirm® layer is very thin, it can be leveraged to provide high-precision bond layers for the thinning process. We have developed a methodology to utilize this approach to provide HPFS wafers with straight tapered vias in thicknesses <150µm (see Figure 2 for an example of a tapered via in 150µm-thick HPFS).

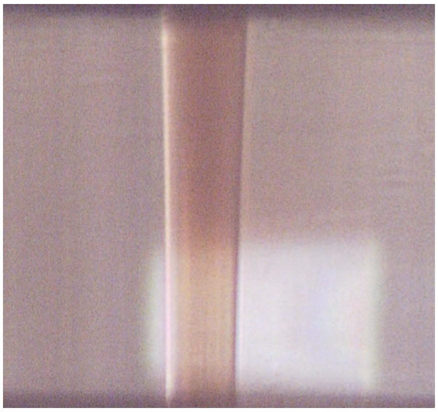

Figure 2: Example of a 30-35µm TGV in 150µm HPFS.

Willow® glass, on the other hand has a moderate loss tangent in the 10-50GHZ range, but provides a practical advantage in that it is manufactured in a large area format, with thicknesses down to 100µm, and with a low surface roughness. This allows you to avoid any grind and polish and provides an opportunity for significant cost savings. Furthermore, it has a CTE of approximately 3.2ppm/°C, which is comparable to silicon allowing the use of silicon handles that are relatively inexpensive and integrate well with existing infrastructure. A few of the properties of both glass types are summarized in Table 1.

Material Property	Glass Type	
	Willow [11]	Fused Silica [12-13]
Modulus (GPa)	74	73
CTE (ppm/°C)	3.2*	0.5**
Dielectric constant	5.3	3.8

*0-300 ºC
**-100 – 200 ºC

Table 1: Glass properties.

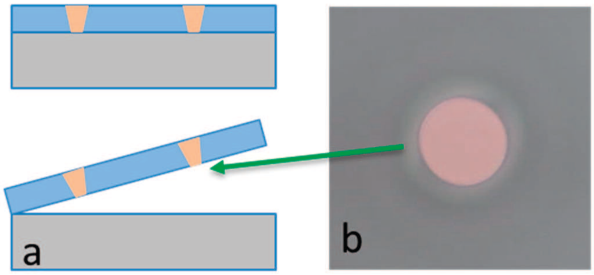

Figure 3: a) Depiction of a debond process showing the region at the base of the via where copper fill detaches from the handle substrate; b) micrograph of the via base region

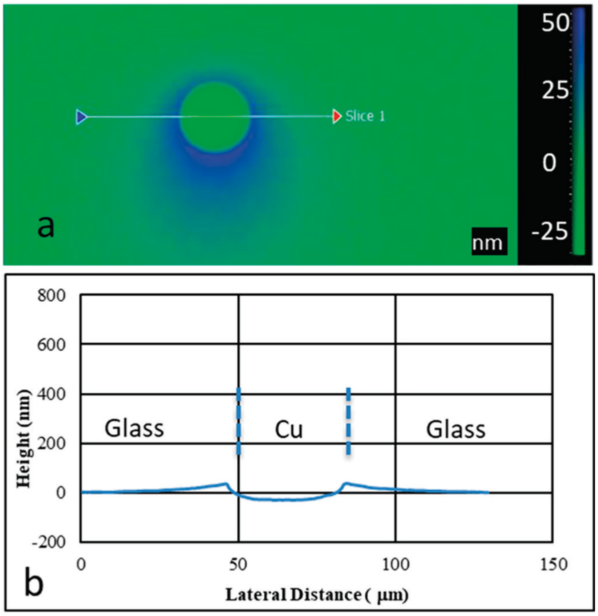

Figure 4: Optical profilometry of a copper fill debond region at the base of the vias. a) Height map of the region showing deviations in height; b) a cross section with heights and delineation of copper and surrounding glass regions, showing that the via-foot is planar to better than 100nm with the glass surface.

Via fill and processing. As illustrated in Figure 1, a via-containing bonded pair can be processed similarly to a silicon wafer. Because the TGVs bonded to a Si handle are essentially blind vias, standard bottom-up plating methodologies can be used to fill the TGVs. Vias have been successfully filled using a physical vapor deposition (PVD) seed process (PVD adhesion layer + PVD copper seed layer) as well as with a metalorganic chemical vapor deposition (MOCVD)-based seed layer process (PVD adhesion layer + MOCVD copper seed). A significant advantage of this approach is that you can achieve void-free vias, which is important for having a reliable product. This is also an important consideration if wafers need to be processed at elevated temperatures because voids in the Cu can cause cracking.

A critical feature of our temporary bond is the ability to debond the device glass from the handle after via fill and retain a suitable morphology of the copper in the via. The sketches in Figure 3a depict the debond operation, illustrating clean separation of the via-filled glass from the handle-wafer. Figure 3b is an optical micrograph of the bottom of a via (via surface facing the handle wafer) after debond, showing a top view of the copper in the via and its apparently smooth surface. In order to assess the topography of the via foot, optical profilometry using the Zygo Zegage ProHR was performed on this base area, shown in Figure 4. Figure 4a shows the topography in top view, with heights as indicated by the associated scale. A slice through the via (Figure 4b) exhibits a very low disturbance from planarity (note the difference in lateral and vertical scales): the entire vertical scale of Figure 4b is 1µm. Root mean square (RMS) roughness of the copper surface was assessed by using a 5µm spatial filter to remove curvature of the surface, and yields roughness values of less than 0.5nm. Therefore, a smooth surface with planar (better than 100nm) filled-via areas is obtained after debond with no further processing.

Via hermeticity is an important aspect for many glass packaging structures, particularly for MEMS applications. We have done preliminary hermeticity assessment on device wafers that have been filled, and had the overburden removed by chemical mechanical polishing (CMP), while using our temporary bonding approach. We characterized two representative wafers. We first characterized the wafer for gross leak through dye penetrant testing. Regions that passed the dye penetrant test were then tested for fine leaks using He leak testing. In this test, the die is exposed to vacuum on one side and helium gas on the other. Leak rates are determined by a calibrated helium leak detector. Three typical die that were tested exhibited leak rates of 1.1e-9atm-cc/s, 3.0e-10atm-cc/s, and 2.2e-10atm-cc/s, respectively. Each of the areas contained a 12 x 11.5mm die with 600 vias.

Simulations for 5G/mm-wafer applications

We have shown that the glass handling approach described above allows for void-free, hermetic vias in thin glass, while the robust temporary bond allows for further processing including CMP, surface metallization, and a clean debond. In order to demonstrate the advantages of glass-based devices in mm-Wave communications, we have worked with Fraunhofer IZM to simulate antenna structures possible with glass using the above processes, as well as simulation of relevant comparison structures possible with PCB materials.

Among the benefits of glass are excellent insulating properties at the mm-Wave frequencies of 5G communications, and a very smooth surface compared with PCB and ceramic substrates, enabling lower RF loss. Additionally, glass is very robust to humidity and temperature fluctuations, and is a highly uniform, homogeneous material with properties consistent across the substrate. Finally, glass manufacturing for the display industry has made large, thin, form factors available, providing significant opportunities for cost-effective and large-area solutions. While we anticipate utilizing both fused silica and Willow® in future applications, the initial simulation work discussed in this paper focuses on fused silica because of its advantaged loss tangent.

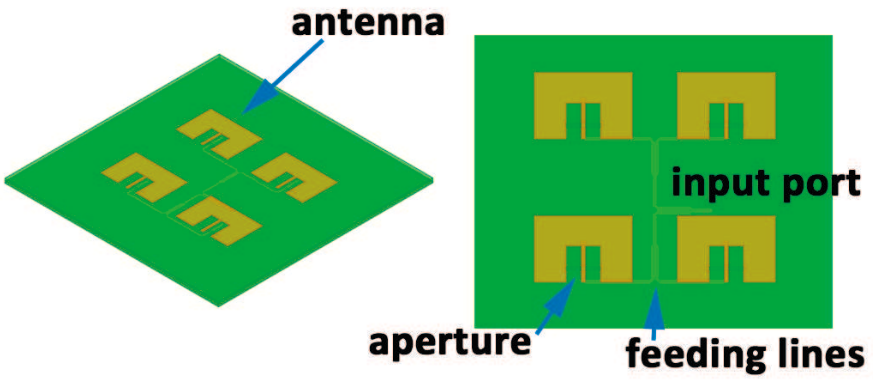

Figure 5: A 28GHz antenna test structure.

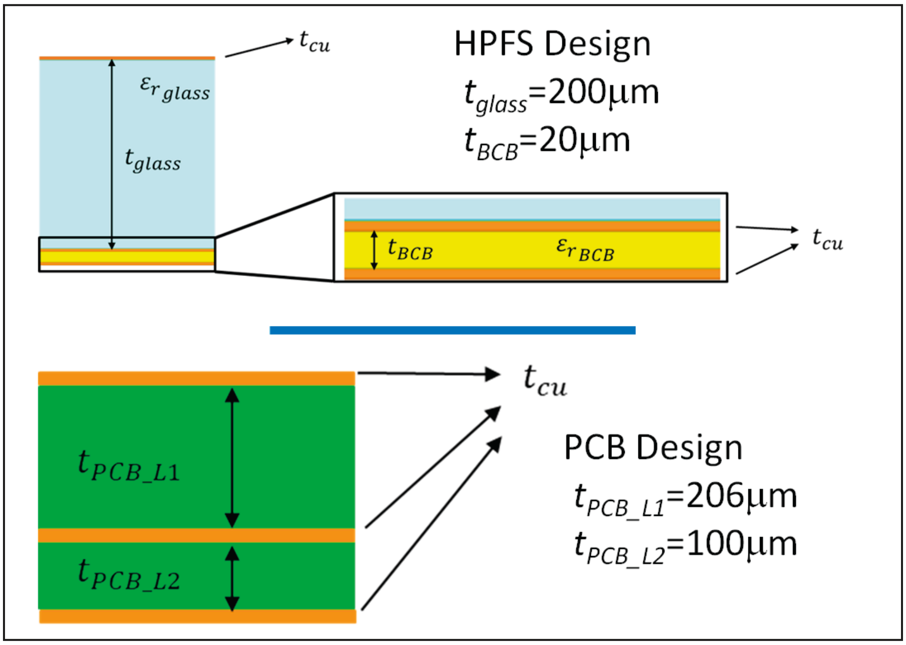

Figure 6: Cross section views of an antenna test structure showing thickness and materials used.

Simulation methodology

The test vehicle used for these simulations is a 2x2 aperture-coupled patch antenna array designed to operate in mm-Wave 5G applications at 20-30GHz. The design is relevant to cellular femtocells, highly distributed base stations intended to operate over 10m-20m distances. Figure 5 shows the basic test structure in perspective and top-down views. The structure contains three copper layers each separated by an insulator: the top layer contains the antennas as listed in the figure, while the bottom layer has the input port and feeding lines, shown shaded in the figure. Between these two metal layers is a ground layer that has an aperture (light green) beneath each antenna that allows coupling of the input signal in the feeding line to the antenna structure. The entire antenna structure is 15.4x15.4mm, while the individual antenna elements are approximately 2.5x3.7mm.

The architectures in cross section are shown in Figure 6, and highlight the different constructions used to achieve the glass- and PCB-based structures. A driving force for the simulation was to maintain thin structures, convenient for a glass-based structure made with our handling solution and useful for general miniaturization. Materials were chosen to achieve this goal as closely as possible within the constraint of having a reasonable path to fabrication.

Another reason to maintain similar thickness structures, and with similar values of dielectric constant ε_r, is that the antenna operating frequency and bandwidth depend on these combined with the planar antenna geometry.

The glass-based antenna simulation uses fused silica glass between the top and middle copper with a thickness of 200µm, while the comparison PCB version uses Panasonic Megtron 6 laminate and Prepreg with a total thickness of 206µm. Both materials have comparable dielectric constants (ε(fused silica)=3.8, ε(PCB)=3.71) while the fused silica does have a lower loss tangent of 0.0002 compared to the PCB at 0.004.

For the insulator between the mid copper layer and the bottom feeding lines, the glass structure uses patterned benzocyclobutene (BCB) at a thickness of 20µm, envisioning a solution-applied insulator consistent with the glass handling-based processes. The PCB structure, on the other hand, leverages the commercially-available Megtron 6 for this part of the stack at 100µm. This thickness disparity is a significant difference in the design parameters, but an offshoot of the desire to keep both structures consistent with available materials and fabrication processes. Finally, a possible advantage of the glass structure is the very smooth surface compared to the PCB, which promotes lower loss conduction at high frequencies [11]. This effect was not included in the simulations and would be more pronounced on the feed network than the patch array because of the long conductor lines.

Simulation results

After both antenna structures were modeled, the bandwidth was assessed by examining the reflection S-parameter, a measure of impedance matching, over the range from 24 to 32GHz as shown in **Figure 7**. The bandwidth, assessed as the region with reflection less than -10db, is similar for both structures, with the glass device exhibiting a bandwidth of 1630MHz while the PCB comparison device exhibits 1670MHz. Bandwidth dictates the ability to maximize the number of communication channels, and the fact that both structures exhibit similar values validates the fact that the materials and dimensions chosen create a suitable comparison.

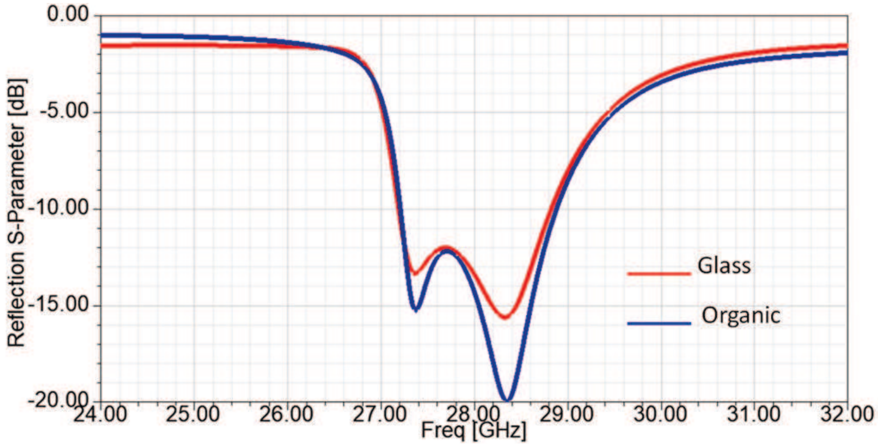

Figure 7: Impedance matching of simulated fused silica (glass) and PCB (organic) structures showing a similar bandwidth for both structures.

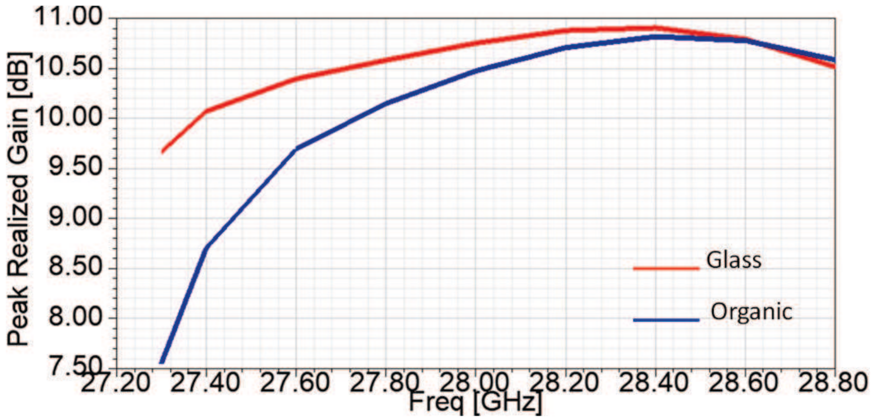

Figure 8: Peak realized gain for simulated fused silica (glass) and PCB (organic) structures, showing a higher and broader gain for fused silica.

Simulation results for the peak realized gain are shown in **Figure 8**, with the frequency axis adjusted to cover only the impedance matching region. For this parameter, it can be seen that the glass antenna not only shows a higher peak gain (10.9dbi vs. 10.5dbi for the PCB structure), but that gain has a broader maximum over the matched frequency band. The increased gain leads to a radiation efficiency of 80% for the glass structure, as opposed to 76% for the PCB version. Based upon these promising results, construction of this antenna structure in both glass and PCB is underway in order to validate the simulation results. While not discussed here, additional simulations show further benefits by using glass in the antenna feed networks because of the low roughness and reduction of losses due to the skin effect. Fabrication of these devices is in process as well.

Summary

We have described a temporary bonding approach that enables processing of thin glass – notably aluminoborosilicate glasses – as well as fused silica. The process allows for a tunable and stable bond energy between substrate and handle, and this bond has been shown suitable for TGV fill as well as for aggressive downstream processes such as CMP.

When a Si handle is used, the bonded stacks mimic Si wafers with blind TGVs. The combined effect makes existing supply chains viable for volume fabrication of thin glass substrates. This has been demonstrated in a number of use cases that includes demonstrating reliable TGV structures that are hermetic and have many advantages for RF/5G, advanced packaging, MEMS and other applications. In particular, the usefulness of such glass substrates to applications in 5G/mm-Wave communications was explored by simulations comparing a fused silica structure to one made with conventional PCB approaches. Promising simulation results validate the value of such glass structures in high-frequency RF communications applications.

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Biographies

David. H. Levy is the Research Director at Mosaic Microsystems, Rochester, NY. He is a chemical engineer with over 25 years of experience in chemical and semiconductor processes. He has contributed in fields ranging from chemical processing to printed electronics development as a Senior Scientist with Eastman Kodak, and was Director of Research and Technology at Natcore with a focus on solar cell technology. He has extensive experience in a variety of deposition methods.

For more information, contact Mosaic Microsystems at info@mosaicmicro.com