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Formation of through-glass vias (TGVs) in glass substrates using femtosecond laser operating in MHz/GHz burst mode

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Abstract

The increasing demand for miniaturized and high-performance consumer electronics has driven advancements in packaging solutions, including the transition to glass interposers. One of the critical aspects of the development is the fabrication of high-density through-glass vias (TGVs). This article presents the formation of TGVs in various glass substrates using an industrial femtosecond laser FemtoLux 30 operating in different operation modes – single-pulse, MHz burst, GHz burst and MHz+GHz burst modes. By employing burst mode and advanced machining methods such as bottom-up milling – TGVs fabrication is possible. With specific parameter sets TGVs with aspect ratios exceeding 1:80 was achieved, with drilling times as low as 350 ms. Additionally, to address current challenges in making electric traces on substrates, it introduces Selective Surface Activation Induced by Laser (SSAIL) as a unique complementary metallization technology, enabling direct copper deposition on different materials like ceramic, plastics and most importantly – glass, for complete packaging workflows. The findings demonstrate the potential of the FemtoLux femtosecond laser as a high-throughput and precise solution not only for TGV fabrication, but also for Selective Surface Activation Induced by Laser (SSAIL) based metallization - supporting next-generation semiconductor advanced packaging solutions.

Keywords: Through glass via (TGV); Femtosecond laser; GHz burst; Percussion drilling; High aspect ratio hole drilling;

1. Future of advanced packaging solutions

There is continuous growth and demand in the consumer electronics field, pushing the limits of integrated circuits (ICs) as never before. To achieve higher chip performance, new innovations such as 2.5D and 3D packaging solutions have emerged. However, several challenges must be addressed first. As chips are stacked, the total thickness of the device inherently increases, which complicates the use of silicon as an interposer [1]. Firstly, thinning silicon interposers through grinding is both expensive and time-consuming [2]. Additionally, silicon's opacity creates difficulties in aligning 3D ICs between solder balls and microelectrodes. Lastly, the differing thermal expansion characteristics of materials can cause deformation, degrading device performance in variable temperature environments [1]. To address these challenges, glass has proven to be a viable alternative for use as an interposer. Glass is rigid, chemically inert, and can be thinned and produced in large, thin sheets relatively economically. Its transparency simplifies the alignment process compared to silicon interposers. Moreover, the thermal expansion coefficient of glass can be tuned, allowing the creation of devices resistant to deformation across different ambient temperatures. Finally, since glass is rigid, it can serve not only as an interposer but, in some 3D packages, as a structural component of the device when used in thicker configurations [2].

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2. TGVs fabrication methods

The challenging part in manufacturing interposers is the highly dense conductive microvias. There are many manufacturing processes that can be used to manufacture through glass vias (TGVs), such as abrasive jet micromachining, abrasive water-jet machining, wet etching, plasma etching, and water-assisted micromachining, to name a few [1]. All of these methods have their own advantages and disadvantages. However, in this article, we focus on laser-based micromachining. Femtosecond lasers are particularly effective for machining brittle and transparent materials due to their short pulse duration, which minimizes thermal load on the material and results in high-quality machining that often requires little to no post-processing. Furthermore, femtosecond laser sources enable non-contact machining, eliminating the need for tool changes and preventing contamination of the substrate. Generally speaking, the most suitable process for manufacturing TGVs depends on the produced shape uniformity and processing time.

In femtosecond laser micromachining, the typical strategy is to ablate material from top to bottom (top-down milling (TDM)) by scanning the desired geometry layer by layer, translating the laser focus deeper into the material until the required depth is achieved (Fig. 1). This method is effective for ablating small features with intricate geometries. However, there are challenges that needs to be addressed. One of the main challenges of the top-down milling method is achieving high aspect ratio geometries - which are particularly important in TGV production, where the aspect ratio is typically around 1:10. This limitation arises due to the many reasons, one of which is tapering from accumulation of ablation debris within the machining area, which limits further material removal and eventually halts the ablation process [3].

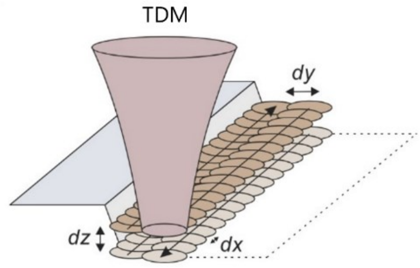

Fig. 1 Schematic of top-down milling method

Another challenge in manufacturing TGVs using the standard TDM approach is heat accumulation. Since energy is concentrated into a small focal spot—typically tens of micrometers in diameter—and the scanning geometry only covers an area two to three times larger than the spot size, the generated heat has limited space to dissipate. This localized heating leads to thermal stress in the material, often resulting in micro-crack formation around the hole's outer edge and between adjacent holes (Fig. 2).

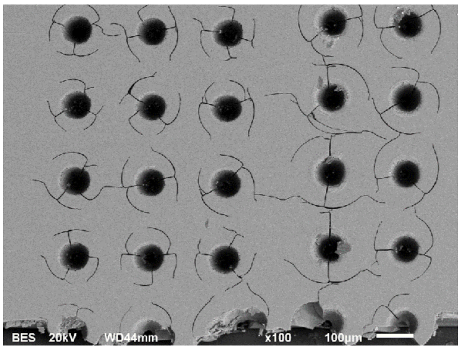

Fig. 2 Observable cracking of glass during small diameter hole drilling (Courtesy of LPKF).

3. Selective laser etching

Selective laser etching is one of the more popular methods for producing TGVs using ultra-short laser sources (Fig. 3). This process consists of two steps: first, locally modifying the glass with ultra-short pulses to create nanogratings, and second, applying a wet etching process where the irradiated volume etches faster than the unmodified areas. This approach allows for rapid modification of the glass panel, followed by wet etching in large basins to achieve throughput suitable for industrial and mass production needs [1]. While this process has been confirmed to work with FemtoLux lasers (Fig. 4), this process involves the use of chemicals, which not only complicates the procedure but also poses safety risks. Therefore, there is an interest from the industry to find alternative methods to produce TGVs.

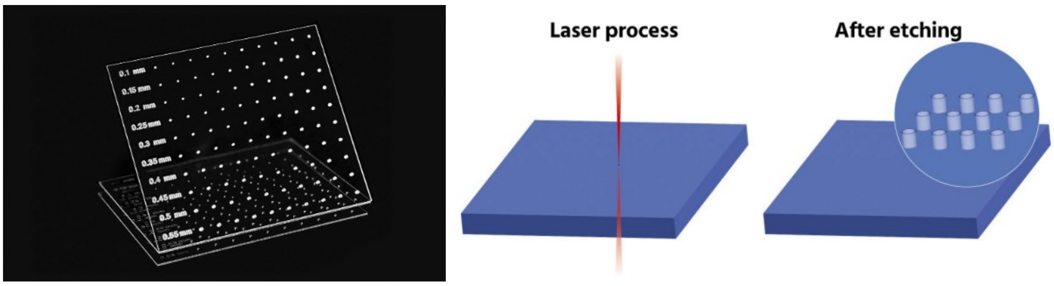

Fig. 3 (left) Selective laser etching of different diameter TGVs in fused-silica glass (Courtesy of Workshop of Photonics).
(right) Schematic of selective laser etching process (Courtesy of RENA Technologies GmbH).

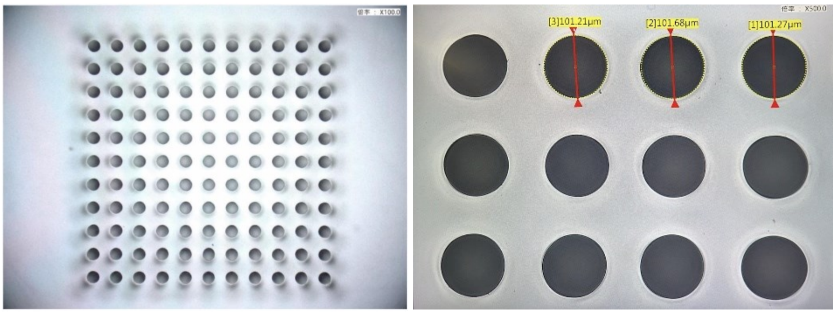

Fig. 4 Selective laser etching of TGVs in 0.7 mm thickness BF33 glass. (left) 100x optical microscope image; (right) 400x optical microscope image (Courtesy of SuperbIN)

4. Bottom-up milling

To address the aspect ratio limitations of TDM, the bottom-up milling (BUM) approach processes the material from the bottom side rather than from the top surface (Fig. 5). Similar to TDM, it operates in a layer-by-layer fashion, but with the focal plane gradually shifted toward the top surface. This configuration allows ablation debris to be efficiently removed from the bottom side of the sample, enabling the formation of high aspect ratio geometries. An example of the flexibility offered by the BUM approach in glass processing is illustrated in Fig. 6. Custom micro-optical elements can be fabricated using a three-step process [4]. First, the substrate is machined from the bottom side of the glass slab. Next, the lens structures are machined directly onto the surface, and finally, to achieve the required optical quality, the surface is polished.

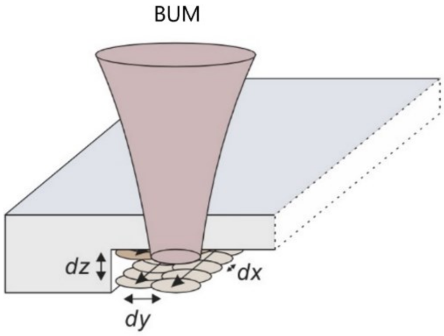

Fig. 5 Schematic of bottom-up milling method

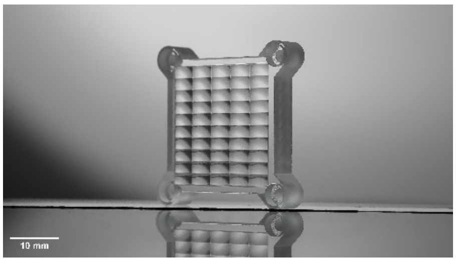

Fig. 6 Micro-lens array machined with combination of TDM and BUM processing methods (Courtesy of FTMC)

5. MHz/GHz burst mode

Femtosecond lasers are known for their high precision, but they typically struggle with throughput. Due to the extremely short pulse duration, the affected interaction volume is significantly smaller compared to longer pulse lasers. This characteristic allows for precise material processing—one of the key strengths of femtosecond lasers—but limits the material removal rate. To overcome this limitation, burst mode has been introduced in modern femtosecond laser systems. In this mode, a single high-energy pulse is split into multiple sub-pulses spaced apart by tens of nanoseconds or hundreds of picoseconds. This division allows the total pulse energy—which would otherwise be too high and risk inducing damage—to be more effectively utilized across several pulses, thereby increasing the overall throughput.

In a study, the influence of burst mode was investigated using various operating modes of the FemtoLux 30 laser for machining fused silica. Two processing methods were compared: traditional top-down milling (TDM) and bottom-up milling (BUM). By systematically varying parameters such as the number of pulses per burst, fluence (energy per unit area), and scanning speed, pockets were machined into fused silica. The ablation rate and efficiency were then determined based on the measured volume of removed material (Fig. 7). The results showed that the highest throughput was achieved using the BUM method combined with a mixed MHz+GHz burst regime.

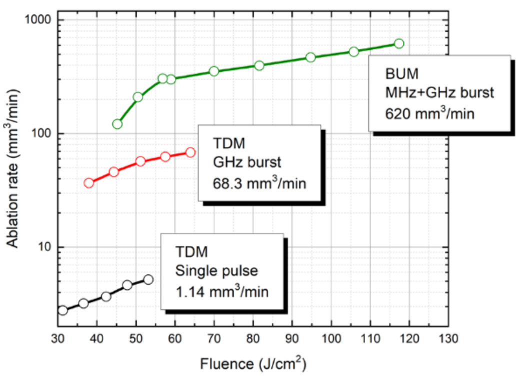

Fig. 7 Graphical representation of ablation rate in various operation modes – single pulse, GHz burst and MHz+GHz burst mode (Courtesy of FTMC)

Table 1. Ablation efficiency and rate at different operation modes and processing methods.

Operation mode	Ablation efficiency, mm³/min/W	Ablation rate, mm³/min
Single-pulse (TDM)	0.27	5.17
GHz burst (TDM)	3	68.3
MHz+GHz burst (BUM)	27.78	619.5

6. Drilling TGVs

6.1. Bottom-up milling

Through-glass vias (TGVs) with a diameter of 60 µm were fabricated in 0.5 mm thick SCHOTT BF33 glass, achieving an aspect ratio of approximately 1:8. The holes were drilled using the bottom-up milling (BUM) approach. To ensure sufficient throughput, a combined MHz and GHz burst mode was initially employed, with a total burst energy of 15 µJ. However, this approach resulted in significant chipping around the hole edges. To reduce this damage, the process was adjusted to a more gentle regime using GHz-only burst mode. Despite the improved parameters, noticeable chipping was still observed, as shown in Fig. 8.

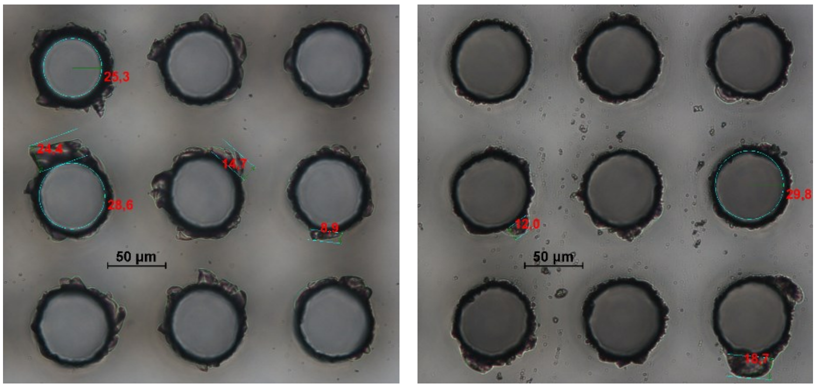

Fig. 8 60 µm diameter TGVs drilled in SCHOTT BF33 glass, resulting in noticeable chipping of ~15 µm. (left) Top surface, (right) bottom surface (Courtesy of FTMC)

To further reduce chipping, shorter wavelengths were employed to take advantage of higher material absorptivity. Without any modifications to the laser source, GHz bursts were successfully generated at a wavelength of 515 nm and used for TGV drilling. As shown in Fig. 9 the use of the shorter wavelength proved effective, resulting in a significant reduction in chipping. Each via was drilled in approximately 1 second. While this may not yet match the throughput of existing industrial TGV fabrication processes, only a fraction of the available pulse energy was utilized. This indicates strong potential for further optimization to increase throughput - without requiring additional post-processing steps such as wet etching.

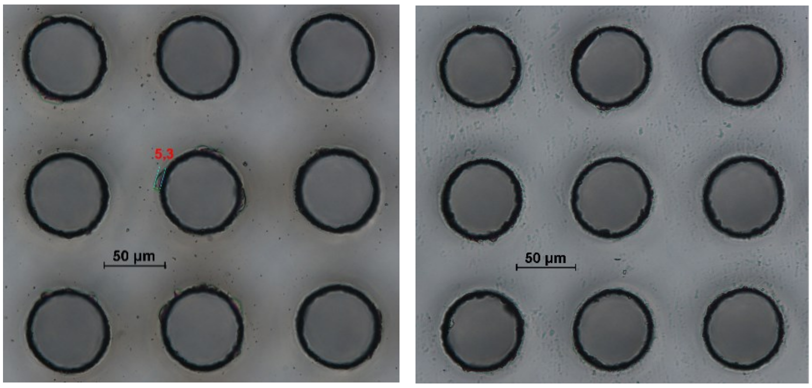

Fig. 9 Impact of GHz burst at 515 nm wavelength on the drilling quality of 60 µm diameter TGVs in SCHOTT BF33 glass. The use of shorter wavelength significantly reduced chipping around the hole edges (Courtesy of FTMC)

6.2. GHz burst drilling

As previously discussed, GHz burst mode plays a critical role in glass micromachining by enabling significantly higher throughput. However, its benefits extend beyond the increase of removal rate. The extremely high pulse repetition rate in the GHz range allows subsequent pulses within the burst to interact with the laser-induced plasma generated by earlier pulses. This interaction opens up new processing regimes, making it possible to fabricate high aspect ratio holes in various materials - structures that would be unattainable using single-pulse mode alone. By leveraging the flexible GHz burst parameter set available in the FemtoLux femtosecond laser series, efficient drilling of high-aspect-ratio TGVs has been successfully demonstrated in multiple types of glass [5].

By splitting a high-energy pulse into 50 sub-pulses with an intra-burst repetition rate of 2 GHz, high aspect ratio hole drilling was demonstrated in 1 mm thick soda-lime glass. As shown in Fig. 11, this technique not only enables the formation of through-glass vias (TGVs) with aspect ratios exceeding 1:80, but also provides precise control over hole depth. This control can be achieved either by adjusting the number of incident bursts or by simply varying the sample's exposure time to the ultrashort laser radiation (Fig. 10).

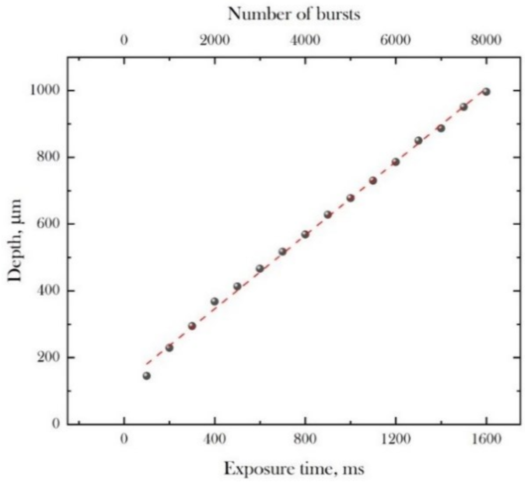

Fig. 10 Hole's depth dependence on the exposure time (Courtesy of Akoneer)

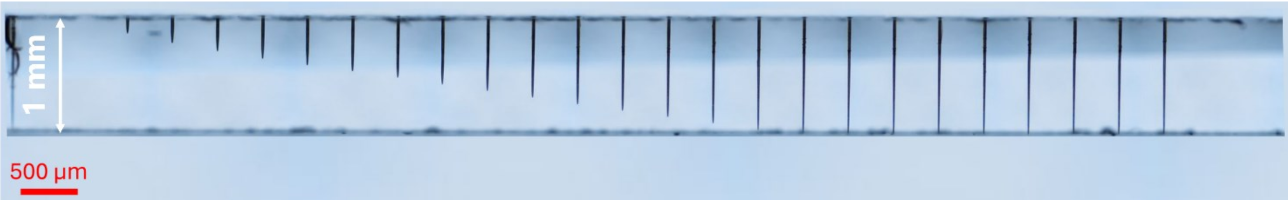

Fig. 11 Drilling of TGVs in 1 mm soda-lime glass. Exposure time increases from left to right (Courtesy of Akoneer).

The performance of this technology was demonstrated across a diverse range of glass materials, including AN100, BK7, BF33, fused silica, soda-lime, and Eagle XG. Each material has different thermal and optical properties, which directly influence the achievable minimum and maximum hole depths. The thermal expansion coefficient plays a key role in determining the likelihood of cracking during percussion drilling, while the material's bandgap limits the maximum achievable depth by defining the absorption efficiency of ultrashort laser pulses. Drilling of a single TGV in 0.5 mm thick glass takes up to 350 ms as of now, with the possibility of downscaling processing time by up to 100-folds by taking advantage of advanced beam splitting techniques.

By combining GHz burst drilling with beam shaping, it is possible to fabricate TGVs with even smaller diameters and higher aspect ratios. As shown in Fig. 12, TGVs produced using this combined technique - long GHz burst drilling and beam shaping – result in near-vertical sidewalls and diameters as small as 1 µm. These vias were formed in 0.5 mm thick glass, achieving an exceptional aspect ratio of 1:500. To verify, the sample was polished from the opposite side until the TGVs were exposed, revealing voids within the modified region and confirming that the holes extended fully through the material. In contrast to the TGVs in Fig. 10, which required multiple bursts per via, these high-aspect-ratio structures were formed using a single long GHz burst with a total energy of 180 µJ - enabling the formation of thousands of TGVs per second.

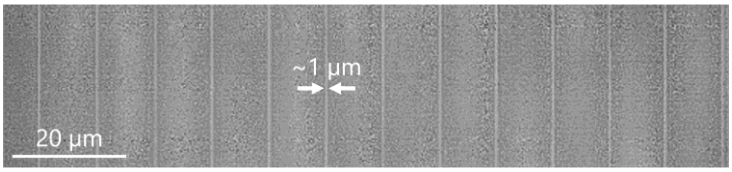

Fig. 12 Drilling of 1 µm diameter TGVs in 0.5 mm thick glass using a single long GHz burst combined with beam shaping. This approach enabled high-aspect-ratio via formation (1:500) in a single laser shot (Courtesy of Akoneer).

7. Electrical traces on any substrate

Beyond via drilling, surface metallization is a critical step in realizing functional interposers and circuit patterns - especially at micron-scale resolution. In the electronics and semiconductor industry, a critical challenge is the ability to create micron-scale electrical traces. While photolithography has long been the standard approach, it comes with complexity and cost. Additive methods like inkjet printing are gaining traction due to their digital and flexible nature, but are currently limited to prototyping or small-scale use because of slower process speeds. There is a clear need for a technology that combines high resolution and throughput with lower cost and process simplicity that can be offered by Selective Surface Activation Induced by Laser (SSAIL) technology [6-7].

SSAIL is a breakthrough technology in this field as it enables creating Cu traces at resolution (1 µm) and throughput similar to lithography but simplifying the process, reducing the cost and being fully digital similarly to additive technologies. High adhesion of SSAIL copper traces to any material also opens up possibilities in display (on glass or transparent films), chip packaging (on PI, ABF, EMC, Si) and PCB (on FR4, FR5) applications.

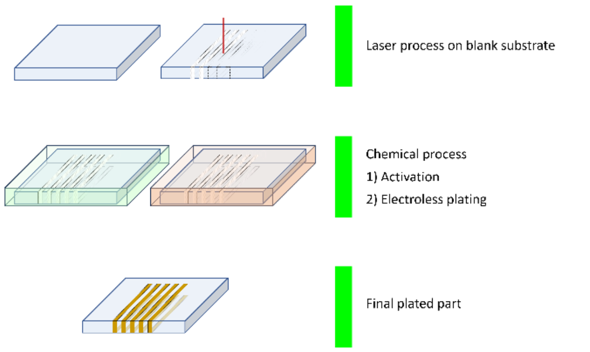

Fig. 13 SSAIL process steps for micro trace formation (Courtesy of Akoneer).

SSAIL technology is an advanced hybrid technology, leveraging ultrashort pulse laser surface modification combined with chemical activation and electroless metal deposition [8]. This process allows direct metallization of non-conductive substrates, eliminating the need for complex photolithographic steps and reducing material waste.

The SSAIL process consists of three primary steps (Fig. 13). First, an ultrashort pulse laser selectively modifies the substrate surface, introducing microscale structural and chemical changes that prepare it for subsequent activation. Next, the laser-modified regions undergo a catalytic activation process, in which they are immersed in a solution containing metal precursors that selectively adhere only to the modified areas. Finally, a self-sustaining electroless process deposits a uniform copper layer only on the activated regions, creating conductive traces with exceptional precision.

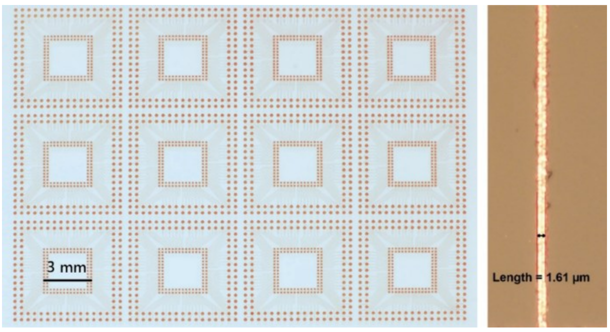

Fig. 14 Fan-out circuit demo on glass material fabricated using SSAIL (Courtesy of Akoneer)

8. Electrical traces on any substrate

Formation of TGVs is one of many steps in whole packaging solutions process chain. After the manufacturing of TGVs, they require selective hole plating, which could be performed effectively by using SSAIL technology. To validate through-hole copper filling, an array of 40 holes with a 0.5 mm pitch and ~ 30 µm diameter was drilled into Eagle XG glass, by utilizing long GHz burst percussion drilling technology. The holes were initially plated, and individual contact pads were formed on the top surface of the sample. On the back surface, a continuous pad connecting all the holes was created, enabling electrical

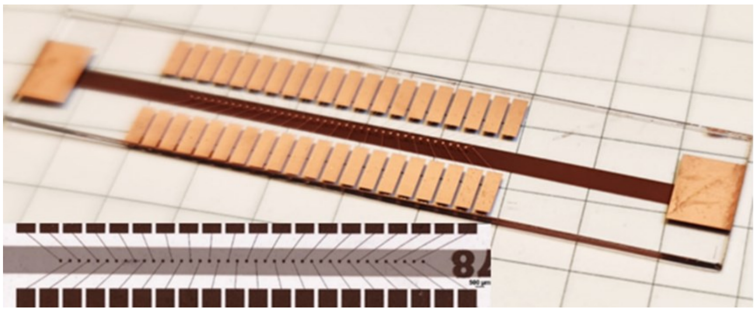

Fig. 15 Metal traces on glass surface connected with laser processed and plated TGVs of 30 µm diameter (Courtesy of Akoneer).

testing of each via in the array. The results demonstrate the compatibility of SSAIL not only in forming high-resolution electrical traces on glass surfaces but also in effectively plating the drilled TGVs.

9. Conclusion

Femtosecond laser technology has proven to be both versatile and effective in the fabrication of through-glass vias (TGVs). Depending on the desired outcome, TGVs can be manufactured using various approaches. For example, combining GHz burst mode with bottom-up milling enables diameter-controlled drilling, which can be further optimized by using shorter wavelengths to reduce chipping and improve hole quality. Alternatively, long GHz bursts can be used to drill high-aspect-ratio TGVs in under a second per via, with precise control over hole depth. Finally, to complete the glass interposer manufacturing workflow, ultrashort pulse lasers can be employed for SSAIL processing—enabling the formation of fine electrical traces and effective metallization of the drilled TGVs.

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