

Material and Integration Requirements of Fused Silica Glass Core Substrates for High-Frequency Packaging

J. Discher¹, C. Wesselkamp¹, L. Hofmann¹

¹ PLANOPTIK AG, 56479 Elsoff, Germany

Glass and quartz core substrates are increasingly considered key enabling technologies for next-generation semiconductor packaging driven by artificial intelligence (AI), high-performance computing (HPC), advanced networking infrastructure, and heterogeneous integration. Compared to conventional organic laminate substrates, selected glass compositions and quartz materials offer improved dimensional stability, favorable coefficient of thermal expansion (CTE) compatibility with silicon, and reduced dielectric loss. These characteristics support fine-line redistribution layers, increased interconnect density, and improved signal integrity.

This paper presents a requirements-driven technical assessment of glass- and quartz-based substrate technologies. Material-related requirements are analyzed with respect to thermomechanical behavior, dimensional stability, and electrical performance. Through-glass via (TGV) integration is discussed as a key enabling technology for vertical interconnect routing, with particular focus on Laser Induced Glass Etching (LIGE) as a state-of-the-art fabrication approach. Furthermore, metallization requirements for glass substrates are examined, including adhesion mechanisms, conformal deposition, and reliability considerations.

Special attention is given to multilayer integration and high-frequency applications, where low dielectric loss and controlled electromagnetic behavior become increasingly important. Quartz substrates are discussed as a particularly attractive platform for frequencies in the approximate 10–100 GHz regime. Finally, manufacturing scalability, process robustness, and quality control requirements are evaluated as critical factors for future industrial adoption.

Keywords— Glass core substrate, Quartz substrate, Through-glass via, Advanced packaging, High-frequency interconnects, TGV, Semiconductor packaging

I. INTRODUCTION

The continuous increase in computing performance requirements for artificial intelligence (AI), high-performance computing (HPC), cloud infrastructure, and advanced networking systems is driving substantial innovation within semiconductor packaging technologies. As package complexity increases and heterogeneous integration becomes more prevalent, conventional organic laminate substrates increasingly encounter limitations related to dimensional stability, thermal expansion mismatch, electrical performance, and routing density.

Recent packaging roadmaps increasingly rely on chiplet architectures, high-bandwidth memory (HBM), advanced redistribution layers (RDLs), and heterogeneous integration concepts. These developments place growing demands on substrate technologies, requiring tighter dimensional tolerances, improved thermomechanical stability, and reduced signal losses. At the same time, larger package formats and increasing I/O densities amplify challenges related to warpage control, process uniformity, and manufacturing yield.

Glass and quartz core substrates have emerged as promising alternatives to conventional organic materials. Depending on composition, glass materials can offer CTE values significantly closer to silicon while maintaining excellent dimensional stability across large substrate areas. In addition, both glass and quartz exhibit favorable dielectric properties that enable improved signal transmission at elevated frequencies. These advantages make them attractive candidates for next-generation advanced packaging architectures.

However, successful implementation of glass-based substrate platforms requires more than favorable material properties alone. The entire process chain, including via formation, metallization, multilayer redistribution, inspection, and reliability qualification, must be considered. This paper therefore presents a structured assessment of the technical requirements and integration challenges associated with glass and quartz core substrates.

II. METHOD (OR INVESTIGATION 1)

This work follows a requirements-driven investigation approach. Rather than focusing on a specific product implementation, the study evaluates the critical technological building blocks required to transform glass and quartz materials into functional advanced packaging substrates.

The analysis is structured along the primary process chain elements. First, material-related requirements are assessed through qualitative comparison of organic laminate substrates, glass materials, and quartz substrates. Evaluation criteria include dimensional stability, thermomechanical compatibility, dielectric behavior, mechanical rigidity, and process maturity.

Second, via integration requirements are analyzed with emphasis on through-glass vias (TGVs). Particular attention is paid to geometric design constraints, aspect ratios, sidewall quality, defect formation mechanisms, and compatibility with downstream metallization processes. Third, metallization requirements are investigated from a packaging integration perspective. Key considerations include seed layer formation, adhesion to glass surfaces, conformal deposition within high-aspect-ratio structures, and reliability under thermal and mechanical stress. Finally, multilayer redistribution concepts, high-frequency design requirements, and manufacturing scalability are evaluated. Special emphasis is placed on panel-level manufacturing considerations, inspection requirements, and yield-critical process steps.

III. RESULTS AND DISCUSSIONS (OR INVESTIGATION 2)

A. Material-Related Requirements and Trade-Offs

Material selection represents one of the most fundamental design decisions for advanced packaging substrates. Compared to conventional organic laminate materials, glass and quartz provide significantly improved dimensional stability and reduced thermomechanical mismatch with silicon.

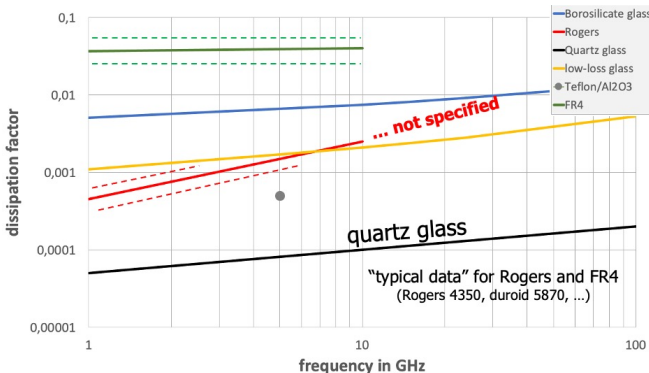


Fig. 1. Comparison between organic materials and glass

These characteristics become increasingly important as redistribution layer dimensions continue to shrink and package complexity increases. Stable substrate geometries improve alignment accuracy during lithography processes and support tighter process tolerances across larger substrate formats.

Electrical performance constitutes another major differentiator. Organic substrate materials typically exhibit higher dielectric losses, which become increasingly problematic at elevated frequencies. A comparison between the dielectric loss of organic materials and glass types is shown in figure 2. In contrast, selected glass compositions offer reduced dielectric loss while maintaining favorable processability. Quartz further extends this performance window due to its exceptionally low dielectric loss characteristics.

frequency	technical glass (borosilicate glass)	Quartz	high frequency board (Rogers 4350)
20 GHz	0,53	0,09	0,20
60 GHz	1,36	0,15	0,44
80 GHz	1,83	0,17	0,55

Fig. 2. Dielectric loss comparison

While organic substrates remain attractive because of established manufacturing ecosystems and favorable cost structures, their electrical and dimensional limitations become increasingly restrictive for next-generation applications. Glass provides a balanced compromise between performance and manufacturability, whereas quartz targets applications where maximum electrical performance outweighs cost considerations.

B. Through-Glass Via Integration and Quality Control

Through-glass vias are among the most critical enabling technologies for glass-based substrate platforms. TGVs enable vertical signal routing, power distribution, grounding structures, and multilayer interconnection schemes. Several competing fabrication technologies exist for TGV generation, including mechanical drilling, abrasive blasting, laser ablation, and Laser Induced Glass Etching (LIGE). Among these approaches, LIGE has attracted significant attention due to its ability to produce high-quality structures with excellent geometric control.

The process combines ultrafast laser modification with selective chemical etching. This approach enables the fabrication of small via diameters, high aspect ratios, smooth sidewalls, and reduced defect densities. Such characteristics directly influence subsequent metallization quality and long-term reliability.

From a design perspective, TGV dimensions significantly affect achievable routing density and process complexity. Smaller via diameters support higher interconnect densities but increase metallization challenges. Conversely, larger vias simplify metallization while reducing available routing area.

A critical challenge associated with TGV implementation is defect management. Microcracks, subsurface damage, and local stress concentrations may propagate during subsequent processing steps. As substrate dimensions increase, even isolated defects can negatively impact overall yield. Consequently, successful TGV integration requires co-optimization of via fabrication, inspection methodologies, and process robustness.

C. Metallization Requirements and Reliability Considerations

Metallization represents one of the most demanding process steps within glass substrate manufacturing. Unlike conventional PCB materials, glass surfaces are chemically

inert and require dedicated adhesion strategies to establish reliable conductive structures.

The metallization process typically begins with seed layer formation. Physical vapor deposition (PVD), sputtering technologies, and dedicated adhesion layers are commonly used to establish conductive surfaces suitable for electrochemical build-up processes.

Subsequent copper deposition must achieve continuous and conformal coverage throughout the entire via structure. As aspect ratios increase, maintaining uniform deposition becomes increasingly challenging. Local discontinuities, insufficient coverage, or void formation may compromise electrical performance and reliability.

From a reliability perspective, metallization systems must withstand thermal cycling, mechanical loading, and long-term environmental exposure. Potential failure mechanisms include delamination, crack formation, increased electrical resistance, and localized degradation of conductive pathways.

These findings indicate that conventional PCB metallization concepts cannot simply be transferred to glass-based platforms. Instead, dedicated process architectures optimized for glass surface chemistry and TGV geometries are required.

D. Multilayer Integration and High-Frequency Design Constraints

Multilayer redistribution structures are essential for advanced packaging architectures. Glass substrates provide excellent dimensional stability and support fine-line routing, making them attractive for high-density interconnect applications.

However, increasing operating frequencies introduce additional design constraints. Closely spaced conductive layers may generate electromagnetic coupling and crosstalk, degrading signal integrity and limiting channel performance. Consequently, layer spacing, shielding concepts, and routing strategies become increasingly important design parameters. Quartz substrates are particularly attractive for high-frequency applications due to their extremely low dielectric loss characteristics. Applications operating in the approximate 10–100 GHz regime, including RF infrastructure, radar systems, satellite communication, and emerging 6G technologies, may benefit substantially from quartz-based interconnect platforms.

The reduced attenuation of quartz-based structures allows longer signal paths while maintaining acceptable transmission performance. Nevertheless, multilayer architectures must be carefully designed to balance routing density, signal integrity, and electromagnetic isolation.

E. Manufacturing Scalability and Industrialization

Although wafer-level processing currently dominates many glass substrate developments, future industrial adoption will increasingly require panel-level manufacturing concepts. Larger substrate formats provide significant economic advantages but simultaneously introduce new challenges. Handling robustness, process uniformity, defect control, and yield management become increasingly critical as substrate dimensions expand.

Inspection strategies therefore become a key enabling factor. Optical inspection, acoustic microscopy, and advanced defect detection technologies must be integrated throughout the manufacturing flow to identify process-induced defects before they propagate into downstream operations. The results indicate that scalability is not solely determined by equipment capability. Instead, successful industrialization depends on coordinated optimization of materials, processes, inspection concepts, and supply-chain readiness.

IV. CONCLUSIONS

This paper presented a requirements-driven technical assessment of glass and quartz core substrates for next-generation semiconductor packaging applications. The analysis demonstrates that glass substrates provide an attractive combination of thermomechanical compatibility, dimensional stability, and electrical performance compared to conventional organic laminate materials. Through-glass vias were identified as a key enabling technology for vertical interconnect integration, with Laser Induced Glass Etching representing a particularly promising fabrication approach due to its ability to generate high-quality structures with low defect densities.

Metallization remains one of the most critical integration challenges. Reliable implementation requires strong adhesion, conformal coverage, and robust performance under thermal and mechanical stress conditions. Furthermore, high-frequency applications place additional requirements on multilayer architecture design and electromagnetic behavior.

Quartz substrates were identified as particularly attractive for applications operating in the approximate 10–100 GHz frequency range, where low dielectric loss becomes a dominant design criterion. Future adoption of glass and quartz core substrates will likely be driven by AI accelerators, heterogeneous integration, advanced chiplet architectures, and next-generation communication systems. Ultimately, scalable manufacturing will depend on the successful co-optimization of material selection, TGV integration, metallization technologies, reliability qualification, and inspection strategies. These factors will determine the long-term viability of glass- and quartz-based substrates as enabling platforms for future advanced packaging solutions.

REFERENCES

- [1] T. Sato et al., “High Aspect Ratio Through-Glass Vias Fabricated by Laser Induced Glass Etching,” *Journal of Microelectromechanical Systems*, vol. 27, no. 3, pp. 456–463, 2018.
- [2] A. Marcinkevicius et al., “Laser-Assisted Fabrication of Through-Glass Vias for Advanced Packaging,” *Applied Physics A*, vol. 124, 2018.
- [3] Y. Chen et al., “Through-Glass Via Technologies: Challenges and Reliability Considerations,” *Microelectronics Reliability*, vol. 88–90, pp. 1213–1220, 2018.
- [4] J. H. Lau, *Advanced Packaging and Heterogeneous Integration*, McGraw-Hill, 2019.
- [5] T. Fukushima et al., “Low-Loss Glass Interposers for High-Frequency Applications,” *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 11, no. 3, pp. 345–353, 2021.
- [6] Industry Report, “Glass Materials in Semiconductor Manufacturing,” 2025.