Advanced Two-Step Filling Approach for High-Aspect-Ratio TGV Structures

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Abstract

The semiconductor industry is steadily moving toward glass-based core substrates to enable substantially higher interconnect densities and to support the larger, more complex system-level packages envisioned for next-generation computing platforms. As ecosystem investment continues toward industrializing glass-substrate technologies, the need for reliable, void-free copper filling in high-volume, glass-based core substrate architectures becomes increasingly critical. In this context, pulse-based single-step filling approaches have shown strong potential to achieve favorable filling behavior when pulse parameters are carefully optimized. However, with decreasing pitch and increasing aspect ratio, the effective electrochemically active surface area rises significantly, making the uniform application of high reverse current densities increasingly challenging, particularly on large substrates.

To address these considerations and to expand the accessible process window, this work introduces a newly developed two-step through glass via (TGV) filling process, consisting of (1) pulse pre-filling followed by (2) DC final filling. The study positions this approach in direct comparison with single-step pulse strategies, highlighting the respective advantages and limitations of both concepts.

A key advancement is the optimization of the DC-filling chemistry through a data-driven additive development approach supported by machine-learning (ML) prediction, enabling identification of suppressor structures tailored for void-free filling. This data-driven approach significantly improves filling stability, low surface deposition, and robustness over a wide dimensional window.

Cross-section and X-ray evaluations on high aspect ratio (HAR) TGV structures confirm consistent, inclusion-free filling for the two-step approach, particularly with respect to seam-void suppression and inclusion control. At the same time, the analysis shows that pure pulse strategies can achieve competitive results when appropriately tuned, while the two-step approach offers advantages in robustness and scalability. The results highlight a trade-off between process simplicity, speed, and defect performance, providing a framework for selecting the optimal filling strategy depending on substrate design and process constraints.

Key words

Advanced Packaging, Copper Filling, High Aspect Ratio, Pulse Reverse Plating, Through Glass Via

I. Introduction

The continued evolution of advanced packaging technologies is driven by the need for increasing functional integration and performance in semiconductor systems. The transition toward system-level integration, particularly for high-performance computing applications, results in significantly larger package sizes and a growing demand for higher interconnect densities. In this context, glass-based core substrates are gaining increasing attention due to their superior dimensional stability and their capability to support fine-pitch routing and high-density vertical interconnections. The realization of such high-density architectures inherently requires TGVs with reduced diameters and tight pitches. At the same time, the use of comparatively thick glass cores leads to increasing aspect ratios of these vias. Consequently, TGV filling processes must address the combined challenge

of high aspect ratio geometries and dense via layouts, placing stringent requirements on both filling performance and process robustness.

A. Technical Challenge

The reliable filling of HAR TGVs without defect formation is a key requirement for ensuring electrical performance and long-term reliability of advanced packaging architectures. In particular, inclusion and void formation during copper electroplating can lead to degraded electrical connectivity and reduced mechanical stability.

These challenges are further amplified in high-volume, glass-based core substrate designs, where large areas with varying via densities—ranging from high-density (HD) arrays to low-density (LD) regions—must be processed simultaneously. In such layouts, achieving homogeneous filling behavior across different density regimes becomes increasingly difficult, as local mass transport conditions and current distribution vary significantly. Beyond these layout effects, a key limitation arises from the increase in effective surface area associated with tight pitch and HAR TGV designs. This directly impacts the applicability of high reverse current densities required in pulse reverse plating, making it increasingly challenging to maintain optimal electrochemical conditions across the entire substrate.

B. State of the Art

Pulse reverse electroplating (PRE) has been demonstrated as an effective approach for copper filling of HAR TGVs. In previous work [7] PRE was shown to give superior throwing power within the via, supporting superconformal filling behavior and enabling defect-free filling for selected geometries.

The alternating forward and reverse current pulses influence electrolyte behavior and enable the formation of favorable deposition conditions inside the via, contributing to improved filling performance.

However, while PRE enables high-quality filling under optimized conditions, increasing via volume and aspect ratio place additional demands on process stability. In particular, the requirement for high reverse current densities in PRE (as reported in [7]) becomes increasingly challenging to maintain as the effective surface area rises with decreasing pitch and higher aspect ratio. This can lead to deviations from the optimal pulse regime, which may result in non-ideal deposition behavior such as premature sidewall closure, seam-void formation, or inclusion formation. Despite these limitations, carefully tuned pulse processes remain a viable and powerful option, particularly when uniform current distribution can be maintained.

C. Contribution of This Work

To address these challenges, this work introduces and evaluates a two-step TGV filling approach, consisting of a pulse-based pre-filling stage followed by a direct-current (DC) final filling stage. The proposed concept is positioned alongside single-step pulse reverse approaches, enabling a direct comparison of both strategies in terms of filling behavior, defect formation, process robustness, and throughput.

In the two-step approach, the first stage uses pulse reverse plating to generate a controlled intermediate via geometry characterized by pronounced centre bridging and uniformity across different pattern densities. In the second stage, the process transitions to a DC-driven filling mode, which leverages this intermediate geometry to initiate a stable, centre-dominated filling mechanism analogous to TSV bottom-up growth.

By separating structure formation from final filling, the two-step strategy provides an alternative pathway to achieve robust, defect-free filling, particularly under conditions where maintaining the optimal pulse regime is challenging. The results of this work highlight the trade-offs between both approaches and provide guidance on their application depending on geometry, layout, and process constraints.

II. Experimental

A. Test Structures

Experimental investigations were conducted on TGV structures with dimensions of 800 µm depth and 100 µm diameter, corresponding to high-aspect-ratio features representative of core-like substrate architectures. The vias were arranged with a center-to-center pitch of 200 µm, allowing the evaluation of filling performance in relatively high-density layouts.

The selected geometry reflects typical requirements for next-generation glass-core substrates, where dense vertical interconnects must be realized within comparatively thick glass materials. Such structures provide a suitable platform to assess the effectiveness and robustness of advanced filling processes under challenging conditions.

B. Plating Equipment

All electroplating experiments were carried out using the same laboratory-scale plating system described in the previous publication. The setup consists of a vertical sparger

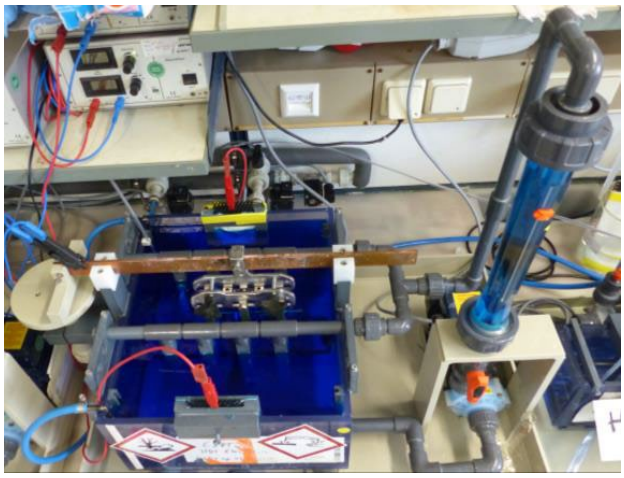

Figure 1 Vertical sparger plating tool 22 liter with knife movement

cell with controlled agitation and knife movement, enabling reproducible mass transport conditions and
uniform electrolyte distribution across the substrate surface. By maintaining identical equipment and hydrodynamic conditions, a direct comparison between the previously reported pulse reverse process and the newly introduced two-step approach can be ensured.

C. *Electrolyte System*

The electrolyte system used in this study is based on the copper sulfate chemistry described in the previous work, consisting of a standard acidic copper plating bath with established additive components for suppressor, accelerator, and leveler functions.
In contrast to the prior study, the present work employs an updated suppressor component, incorporating a newly developed molecule within the additive system. This modification was specifically introduced to enhance the tuning of surface and via deposition behavior in combination with the two-step filling strategy.

D. *Development of the Suppressor System*

To further enhance the performance of the DC final filling step, a dedicated suppressor system was developed based on a combination of experimental screening and data-driven analysis.

An initial library of approximately 60 in-house synthesized molecules was evaluated in model through silicon via (TSV) filling experiments. The performance of these molecules was assessed with respect to their ability to enable uniform, void-free filling behavior under DC conditions.

To enable a more consistent and scalable evaluation of filling performance, optical cross-section images of the filled vias were analyzed using a machine-learning-based image recognition approach. In this workflow, individual via cross-sections were automatically processed and classified according to characteristic filling features such as seam void formation, inclusion density, and degree of conformality. Based on these features, each sample was assigned a quantitative filling quality score, allowing a standardized comparison across all tested suppressor candidates.

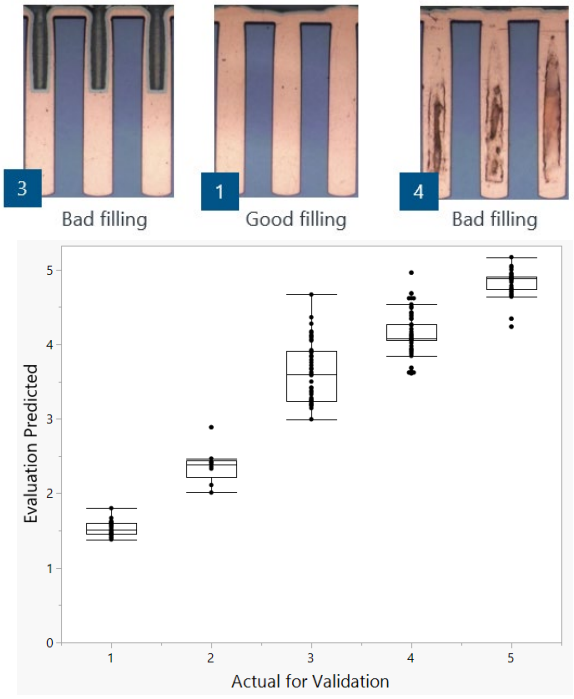

Figure 2 TSV test structures with different filling rates from 1 - good filling to 5 worst filling. Graph: Validation of manual rating vs. machine rating

The resulting dataset—linking molecular candidates to image-derived filling scores—was used to train a predictive model capable of ranking and classifying suppressor performance. This approach reduces subjective bias in visual evaluation and enables a more robust identification of high-performing additives across a wide range of experimental conditions.

Based on the model predictions and ranking results, new suppressor candidates were designed and synthesized in-house, targeting the chemical design space associated with improved filling behavior. These newly developed molecules were subsequently validated experimentally under identical plating conditions.

The resulting suppressor system demonstrated a significant improvement in DC filling performance, particularly in combination with the two-step process approach. In contrast to earlier candidates, the optimized suppressor enabled effective suppression of surface deposition while promoting very high copper deposition rate in an intentionally non

bridged, worst-case scenario, conformally prefilled TGV structure.

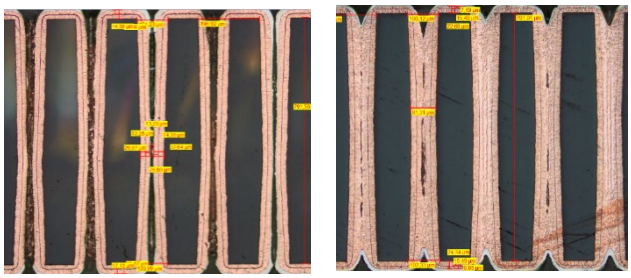

Figure 3 Conformally prefilled test structures. Left side: DC filling result with standard suppressor, right side: DC filling with new suppressor.

This iterative workflow—combining experimental screening, automated image-based evaluation, and model-guided candidate selection—provides a practical pathway for developing electrolyte additives tailored to specific filling concepts, enabling improved robustness and filling performance in high-aspect-ratio TGV structures.

III. Process Concept: Two-Step TGV Filling

A. Rationale for a Two-Step Approach

In our previous work, PRE was shown to be an effective method for enabling bridging and superconformal filling behavior in HAR TGVs, while mitigating inclusions and voids through alternating forward and reverse current pulses. When the pulse parameters are properly tuned, this single-step approach can deliver strong filling performance and represents an attractive, process-efficient solution.

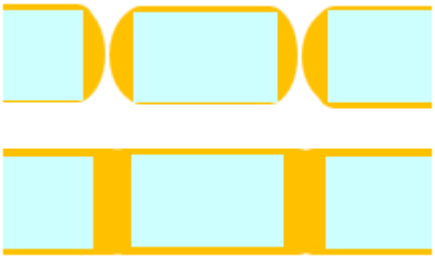

Figure 4 Concept of one-step filling

However, the PRE mechanism relies on the application of sufficiently high reverse current densities to establish the desired deposition dynamics. With decreasing pitch and increasing TGV aspect ratio, the effective surface area increases substantially, making it increasingly difficult to apply these currents uniformly across large substrates. Under such conditions, the process may deviate from its optimal operating regime, increasing sensitivity to local mass-transport and current-distribution variations and potentially promoting seam-void and inclusion formation.

To address these limitations while preserving the benefits of pulse-based initiation, the filling can be separated into two dedicated stages with distinct roles: (1) pulse pre-filling to deliberately create a favorable intermediate geometry (centre bridging), and (2) DC final filling to complete via closure through a stable centre-initiated mechanism. This decoupling separates "geometry preparation" from "completion," enabling improved controllability and robustness, particularly for complex layouts with varying via densities.

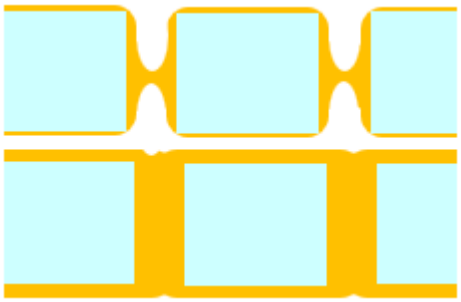

Figure 5 Concept of Bridging+Filling

B. Step 1 — Pulse-Reverse Bridging

Step 1 is designed to intentionally form a strong bridge in the centre of the TGV, creating an intermediate structure that prepares the via for robust DC completion.

A key enabler of this stage is that pulse reverse operation generates cuprous ions (Cu(I)) during the reverse portion of the waveform, which has been identified as an important factor influencing accelerated filling behavior and void mitigation in high aspect ratio features. In addition, PRE-specific effects—including additive redistribution during reverse pulses—support preferential deposition behavior that promotes bridge formation within the via.

In the two-step strategy proposed here, process parameters are tuned specifically to maximize controlled bridge growth at the TGV centre, including:

- the pulse waveform (forward/reverse components and current levels),
- flow/convection conditions,
- temperature.

The targeted outcome is a reproducible, well-positioned centre bridge that is consistent not only within a given via field, but also homogeneous between HD and LD areas on the same substrate. This HD/LD homogeneity is critical for high-volume, core-like substrate layouts, where local pattern density differences otherwise tend to translate into density-dependent fill variability.

Resulting intermediate geometry: The via after Step 1 exhibits pronounced centre bridging, creating a TSV-like precursor geometry that effectively "re-defines" the subsequent filling problem from a long HAR via into a more favorable completion task.

C. Step 2 — DC Final Filling (Center-Initiated TSV-Like Growth)

Step 2 completes the filling by initiating a TSV-like centre-driven growth mechanism under DC conditions. The process starts from the bridged TGV centre and propagates in a bottom-up manner, avoiding uncontrolled sidewall closure.

A key enabler is a newly developed suppressor molecule, identified and optimized through a machine-learning-supported, data-driven screening approach. The resulting DC chemistry provides two critical effects: suppression of surface deposition and promoted metal growth at the TGV centre, enabling a stable, inclusion-free filling mechanism.

Based on the low-convection, pre-bridged geometry established in Step 1, the process reliably transitions into a centre-anchored growth regime, resulting in dense, void-free copper filling with minimized surface deposition and high repeatability across varying layout densities.

IV. Results and Discussion

A. Reference: PRE-Only Process

The PRE-only results demonstrate generally uniform filling with good overall performance. A slight seam void is observed along the centerline of the vias; however, the defect size remains limited and does not significantly impact the overall filling quality.

The inclusion volume is below 1%, indicating effective suppression of major defect formation despite the extended deposition process.

The plating time was 8.5 hours, which appears to be slightly insufficient, resulting in a minor recess at the via top. For complete filling, a plating time of approximately 9 hours is expected

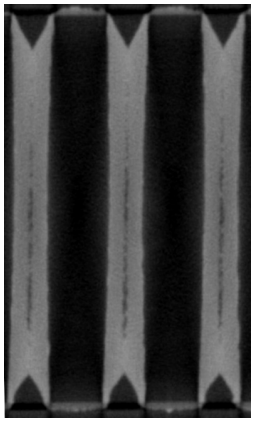

Figure 6 Result of one-step filling in x-ray

B. PRE + DC Process

The PRE + DC results demonstrate a highly uniform filling behavior with improved center stability compared to the PRE-only approach. No pronounced seam void is observed, and the filling appears dense and continuous across the via cross-section.

The inclusion volume remains below 1%, and the total plating time exceeds 12 hours, indicating a significantly longer process duration compared to the PRE-only case. This extended plating time is associated with the controlled DC filling step, which stabilizes the filling front and suppresses seam formation.

Overall, the results indicate that the PRE + DC approach enables robust void-free filling with improved structural quality, albeit at the expense of significantly increased process time and higher surface copper deposition of about 30µm.

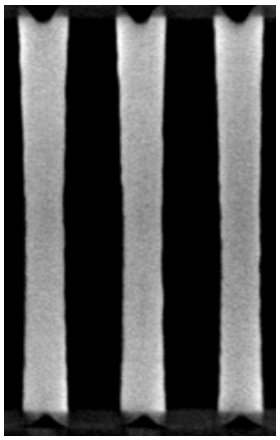

Figure 7 Result of two-step filling in x-ray

V. Conclusion

The two-step filling process was successfully demonstrated as an effective approach for HAR TGV structures. The separation into pulse pre-filling and DC final filling enables controlled bridge formation and robust centre-initiated via completion, resulting in inclusion-free and seam-void-free filling behavior.

In comparison, single-step pulse processes remain a highly capable and efficient solution when the required pulse conditions can be maintained, offering advantages in process simplicity and speed. However, their performance can become increasingly sensitive under conditions of high effective surface area and complex layout distributions. The results of this study demonstrate that both approaches have distinct advantages and limitations, with the two-step strategy providing enhanced robustness and defect control, while pulse-only approaches offer potential benefits in

throughput. This comparison provides a framework for selecting the appropriate filling strategy depending on geometry, substrate size, and process requirements.

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