Pulse Reverse Electroplating for Copper Filling in High Aspect Ratio Through Glass Vias for Advanced Packaging

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Abstract

Heterogenous integration enables increased functional density by integration of multiple chips or components into a single package. This integration leads to an increase of the overall package size and is a challenge for the dimensional stability of the package. One potential solution to this challenge is the application of new materials like glass to provide unparalleled flatness and dimensional stability. Inclusion-free filling of high aspect ratio (HAR) through glass vias (TGVs) is crucial for significantly enhancing the performance and reliability of advanced electronic packaging.

This study explores the application of pulse reverse electroplating (PRE) to achieve defect-free copper electroplating in HAR TGVs. Defect-free filling of HAR TGVs is vital for the performance and reliability of advanced electronic devices. Addressing this issue directly impacts the efficiency and longevity of the packaging products. The PRE technique, which utilizes alternating current pulses combined with advanced DC electroplating processes, effectively mitigates the formation of inclusions and voids, ensuring excellent bridging and superconformal filling even in challenging structures.

The study examines more complex PRE techniques to achieve conformal filling for small features in interposer-like structures. Our study shows that these methods can provide inclusion-free filling for certain through hole dimensions, as verified by x-ray investigations. The data demonstrates PRE's potential to enhance structural integrity and improve thermal and electrical conductivity.

Future research will focus on refining these processes to accommodate diverse structure dimensions, further enhancing their reliability and versatility. By refining the techniques and exploring new combinations of electroplating methods, including testing new in-house synthesized molecules with tailored electrochemical performance, we aim to further enhance the versatility and reliability of HAR TGV filling processes to meet the evolving demands of advanced electronic packaging.

Key words

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

Introduction

In the rapidly evolving field of electronics, advanced packaging technologies have become crucial for enhancing the performance, functionality, and miniaturization of electronic devices. Advanced packaging involves integrating multiple chips or components into a single package, enabling increased functional density and improved electrical performance. This heterogeneous integration is essential for meeting the demands of modern electronic applications, such as AI computing, telecommunications, and consumer electronics.

One of the significant challenges in advanced packaging is maintaining the dimensional stability and flatness of the package, especially as the overall package size increases [1]. Traditional organic materials, while cost-effective and customizable, are prone to warpage due to their flexibility and differences in the coefficient of thermal expansion (CTE) between the silicon chip, molding compound, copper, polyimide, and other materials. Warpage can lead to issues such as cracking, delamination, and misalignment, compromising the reliability of the package.

To address these challenges and reduce production costs, researchers and engineers are exploring the use of new materials, with glass emerging as a promising candidate. Glass offers several advantages over traditional materials in advanced packaging. Its unparalleled flatness and dimensional stability make it an ideal substrate for high-precision applications. Glass is also chemically inert, has excellent thermal stability, and can be manufactured with high optical transparency. These properties make glass suitable for a wide range of applications, including high-frequency and high-speed electronic devices. Additionally, glass is significantly cheaper than silicon, making it a cost-effective alternative for manufacturers.

However, the introduction of glass as a substrate material in advanced packaging also presents several challenges. One of the primary challenges is the inclusion-free filling of high aspect ratio (HAR) through glass vias (TGVs). TGVs are vertical interconnections that pass through the glass substrate, enabling electrical connections between different layers of the package. Achieving defect-free filling of HAR TGVs is crucial for ensuring the performance and reliability of the package. Traditional electroplating techniques often struggle with issues such as void formation, non-uniform filling, and poor adhesion, which can compromise the integrity of the package.

To overcome these challenges, this study explores the application of pulse reverse electroplating (PRE) for copper filling in HAR TGVs. PRE utilizes alternating current pulses combined with advanced direct current (DC) electroplating processes to mitigate the formation of inclusions and voids. Two primary theories explain the mechanisms behind the effectiveness of PRE: the desorption and re-adsorption of additives [2], and the generation of cuprous ions during the reverse pulse. Understanding these mechanisms is crucial for optimizing the PRE process and improving the performance of the filling process.

Theoretical Background

Desorption and Re-adsorption of Additives

One theory [3] explaining the effectiveness of PRE involves the desorption and re-adsorption of additives during the reverse pulse. During the reverse pulse, suppressing species (S) on the panel surface or near the via opening are desorbed [4], allowing for fast resorption of suppressing species when the forward plating is restored. This process helps in forming a bridge in the center of the through via, enhancing the filling quality.

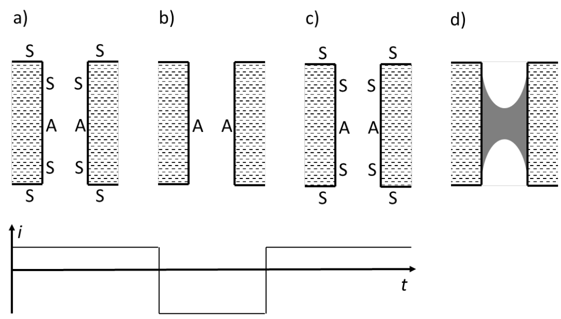

Figure 1 . Schematic representation of additive action on copper deposition inside a through via during reverse pulse plating: suppressing species (S) dominate on panel surface, while accelerating (A) – in through via center (a); during reverse pulse predominantly additive species on panel surface or close to via opening are desorbed (b); restoring to forward plating allows for fast resorption of suppressing species on panel surface (c); net effect of reverse pulse plating is bridge formation in the center of through via (d).

Generation of Cuprous Ions

Another crucial mechanism is the generation of cuprous ions (Cu(I)) during the reverse pulse, according to (1). Generally, electrolytic copper disso According to Kondo et al. [5], the cuprous ion concentration increases significantly during the reverse portion of a periodic reverse pulse waveform. This increase in cuprous ions is essential for achieving accelerated filling and reducing voids during copper electrodeposition. The study by Kondo et al. demonstrated that additives such as bis-(3-sulfopropyl) disulfide (SPS) and chloride enhance the production of cuprous ions, forming an acceleration complex (Cu(I)-thiolate) that accumulates at the electrode trench bottom. This complex plays a vital role in accelerating copper electrodeposition, particularly in high aspect ratio structures like TGVs.

$$Cu \rightarrow Cu^{+} + e^{-} \qquad (1)$$

$$Cu \rightarrow Cu^{2+} + 2e^{-} \qquad (2)$$

Furthermore, Koga et al. [6] highlighted the importance of controlling Cu(I) accumulation in copper sulfate electroplating solutions. Their research showed that the accumulation rate and amount of Cu(I) depend on factors such as current density, electrolysis time, and the type of dissolved gases. By managing these conditions, it is possible to optimize the Cu(I) concentration in the plating solution, thereby improving the quality of the copper plating film.

Electrochemical Measurements

To understand the relationship between reverse current density and cuprous ion generation, a series of electrochemical measurements were conducted. These measurements aimed to quantify the generation of cuprous ions (Cu(I)) under varying current densities and convection conditions.

Experimental Setup

The generation of cuprous ions dependent on anodic current density was investigated using a platinum rotating disc electrode (RDE) with a diameter of 2 mm. All experiments were conducted at room temperature. A platinum rod served as the counter electrode. The electrolyte solution consisted of 55 g/L copper, 85 g/L sulfuric acid, and 90 mg/L chloride. Copper deposition was performed for 300 seconds at an anodic current density of 1 ASD. Stripping was conducted galvanostatically with varying current densities. A Metrohm Autolab potentiostat was used to control the electrochemical processes.

Results and Discussion

The results, as depicted in the accompanying graph, indicate that with increasing stripping current density, the current efficiency decreases. This trend suggests a higher generation of cuprous ions at elevated stripping current densities

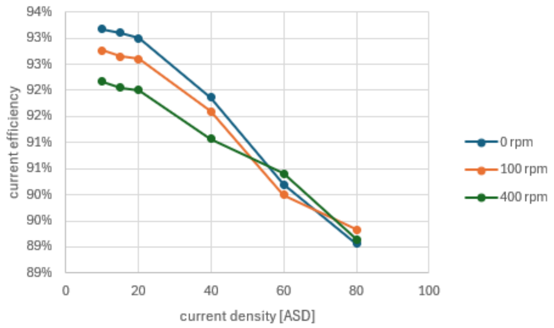

Figure 2 charge efficiency for copper stripping with various current densities.

The electrochemical measurements revealed a clear dependency between reverse current density and cuprous ion generation.

Impact on TGV filling quality

Our findings demonstrate the effectiveness of PRE in achieving high-quality filling and its potential to improve the reliability and versatility of advanced electronic packaging. Combining in house synthesized additive systems with tailored pulse shapes gives the opportunity to optimize defect free TGV filling for a wide range of dimensions and via shapes.

Experimental Setup

To optimize the filling of high aspect ratio (HAR) through glass vias (TGVs), experiments were conducted using pulse reverse electroplating (PRE) in a 22 liter lab sparger tank with knife movement. A Plating Electronics pulse rectifier was used to generate various pulse shapes to optimize cuprous ion generation and optimal filling conditions with it. The focus was on adjusting the reverse current density to achieve defect free filling conditions. To further support the filling and tailor the performance regarding surface distribution and appearance the additive system was adjusted to meet our internal quality criteria.

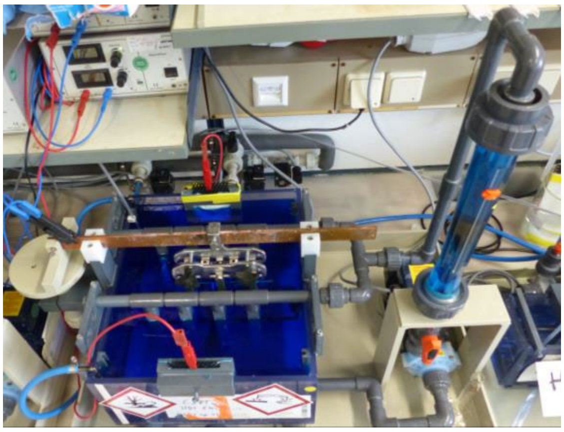

Figure 3 Vertical sparger plating tool 22 liter with knife movement

Plating time was 4 hours at room temperature with sparger agitation and knife movement.

Results and Discussion

Inclusion free filling was demonstrated for dimensions of interposer-like through glass vias, as shown in the following cross sections and x-ray investigations.

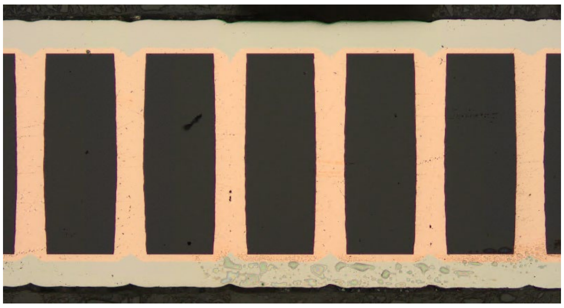

Figure 4 cross section of 400x70 µm through glass via with a center-to-center pitch of 200µm

As seen in the x-ray, no inclusions are formed in the fully filled through glass vias.

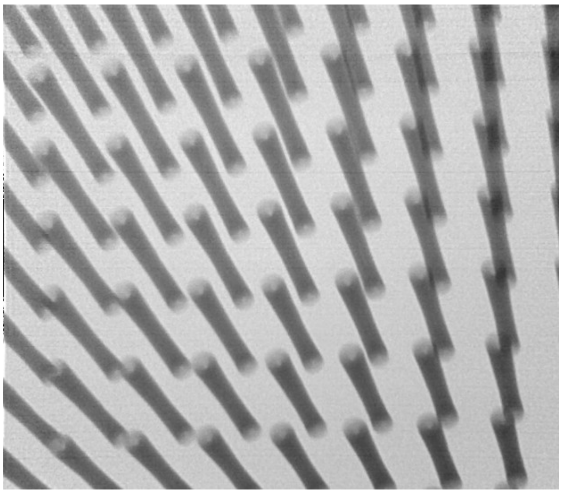

Figure 5 high resolution x-ray of the sample from figure 4 proofs defect-free filling

Conclusion and Outlook

This study has demonstrated the effectiveness of pulse reverse electroplating (PRE) in achieving high-quality copper filling in high aspect ratio (HAR) through glass vias (TGVs). By leveraging the desorption and re-adsorption of additives and the generation of cuprous ions during the reverse pulse, PRE significantly enhances the filling quality, reduces void formation, and improves the reliability of advanced electronic packaging. The experimental results confirm that PRE can achieve defect-free filling across various TGV dimensions, making it a promising technique for future applications in heterogeneous integration and advanced packaging technologies.

Looking ahead, further optimization of the PRE process will focus on expanding its applicability to an even wider range of dimensions and TGV shapes. By fine-tuning the pulse shapes, current densities, and additive systems, we aim to enhance the versatility and performance of PRE for diverse packaging requirements, paving the way for more efficient and cost-effective manufacturing processes in the electronics industry.

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